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### **Compact High Frequency Radars for Increased Maritime Domain Awareness**

Coordinated networks of Compact High Frequency Radars, deployed on shore and on buoys, are now a viable gap-filling technology that could be configured to increasingly support Coast Guard and other Homeland Security needs for Maritime Domain Awareness through improved wide-area vessel surveillance and simultaneous environmental data collection. Maritime Domain Awareness to support Port Security includes the need for wide area surveillance systems to identify the location of all vessels within a region of interest, and the ability to compare this field with the voluntary Automatic Identification System (AIS) reporting network to improve the targeting of specific vessels for inspection or intervention. Intervention activities require putting Coast Guard personnel to sea on vessels or aircraft. Maritime Domain Awareness includes knowledge of the environmental conditions within an operational area to minimize the safety risks to responding Coast Guard personnel. In the unfortunate event of an incident, real-time environmental data is required to cue response teams for Search And Rescue efforts and to minimize further environmental impacts.

Compact High Frequency (HF) radars are a widely accepted technology for environmental data collection, providing a unique current mapping capability and an inexpensive alternative for wave monitoring. Ongoing research at the Sandy Hook, New Jersey, HF Radar Testbed has demonstrated that Compact High Frequency (HF) Radars can simultaneously extend vessel detection and tracking capabilities over-the-horizon, well beyond the line-of-sight coverage of conventional Microwave Radars. This dual-use capability, combined with the lower cost and risk of a distributed network of compact HF radars, has prompted the formation of a collaborative government-academic-industry partnership to continue to refine and demonstrate new HF Radar technologies. The partnership's successes in the development and demonstration of a dual use technology that is now available to improve operations has attracted the attention of the international community, in particular the Norwegian military. Further investment in both the research partnership and the eventual operational agency could be directed to more rapidly transition Compact HF Radar technology into increasingly widespread use for Maritime Domain Awareness to improve Port Security.

### **Background**

High Frequency (HF) Radars were first constructed during World War II in England in an attempt to detect approaching German aircraft. These early radars were designed to broadcast a radio signal in the HF band towards Europe, and then use a receiver antenna array 100's of meters long to acquire the backscattered signals from the intended targets. Unfortunately, the radars were "jammed" by a large signal from an unknown source that overpowered the expected hard target returns. In the middle 1950's, it was discovered that the jamming signals were not clever German counter-measures, but

actually were HF radar signals that scattered off of surface waves in the North Sea. The process is known as Bragg Scattering.

Bragg Scattering occurs when the roughness elements causing the scattering are spaced at one-half of the wavelength of the transmitted radio signal. When this occurs, the backscattered signals from each roughness element are in phase and reinforce each other, producing what is known as a Bragg peak in the return signal. For HF radars, the typical broadcast frequencies range from 5 to 25 MHz in a portion of the spectrum located between the AM and FM radio bands. The wavelength of these broadcast signals ranges from 60 m to 12 m, with Bragg scattering occurring over ocean waves half as long. But ocean surface waves are not stationary. They propagate at well known speeds based on their wavelength. The backscattered Bragg peak associated with moving ocean waves experiences a Doppler shift. Just like the sound from a passing vehicle, surface waves moving towards the radar result in a slightly higher frequency Bragg peak, and surface waves moving away from the radar result in a slightly lower frequency Bragg peak. An additional Doppler shift occurs if the surface waves are also riding an ocean current. Again, the frequency of the Bragg peak is increased if the current has a component towards the radar, and is decreased if the current has a component away from the radar.

Recognition of this physical process in the 1970's prompted the additional development of HF radars as tools for mapping ocean currents. For current mapping applications, two or more radars distributed along the shore are required. Each radar measures the component of the current moving in the radial direction towards or away from itself. In regions where the radial current coverage from at least two radars overlaps at angles approaching 90 degrees, the total current vector can be estimated from its observed components. As in hard target tracking applications, the early radars required a long linear receiver array measured in 100's of meters. Just as all microwave radar receivers are many times longer than the few centimeter wavelength of the microwaves, the early HF radars all used linear phased arrays many times longer than the HF wavelength to aim the radars in a specific direction.

At this point it was recognized by NOAA scientist Dr. Donald Barrick that large phased arrays were impractical for widespread use. Because the decay of the HF groundwave is extremely rapid over dry land, HF radars need to be located within a few wavelengths of the salt water to take advantage of their over-the-horizon view. Because the biggest NOAA markets for current maps were expected around busy ports and population centers where beach and waterfront real estate was at a premium, it was expected there would be little tolerance for the installation of networks of large linear antenna arrays. To solve this problem, Dr. Barrick invented compact HF radars, and formed the company CODAR Ocean Sensors to develop and market the product. Using the direction finding properties of circular rather than linear arrays, CODAR HF Radar receivers can fit on a single post deployed near the water on a beach, dune, dock or cliff. Today, CODAR Ocean Sensors is the largest manufacturer of HF radars in the world.

In the 1990's, Rutgers University and CODAR Ocean Sensors formed an academic-industry partnership for the development of HF radar and its products through the support of the National Ocean Partnership Program. That partnership is now in its 9<sup>th</sup> year, focusing on the design, testing and rapid transition of the dual-use capabilities of compact HF radars. In this case, dual-use means both environmental products (currents and waves) and vessel tracking products. Today, the Rutgers University (R.U.) Coastal Ocean Observation Lab (COOL) operates the most advanced HF radar network in the world. The CODAR network is used to map ocean currents over the New Jersey continental shelf and the entrance to New York Harbor, to monitor waves and alongshore currents on the New Jersey coast, and to testbed new vessel tracking capabilities for homeland security, counter narco-terrorism, and naval applications.

### **Environmental Applications**

For HF radars, the Doppler spectrum of the return signal produces a Bragg Scattering peak with a main center lobe and smaller secondary lobes on either side. The Doppler shift of the main center lobe is used to calculate ocean currents, and the smaller sidelobes are used to calculate surface wave parameters. The range and resolution of the radars is determined by its broadcast frequency, with lower frequencies producing longer ranges, and higher frequencies producing higher resolution.

Rutgers operates two CODAR HF radar current mapping networks in New Jersey. The 5 MHz long-range network provides current mapping coverage of the entire continental shelf offshore New Jersey. The 25 MHz high-resolution network provides high resolution nested coverage of the entrance to New York Harbor. Both networks were installed to support environmental research activities, attracting scientists from around the world. The environmental datasets are displayed on the R.U. COOL website (<http://marine.rutgers.edu/cool>) in real time for use by the general public. The nested high-resolution CODAR network is used by the NOAA fisheries groups based at Sandy Hook to improve their sampling, and by the New Jersey Department of Environmental Protection to observe the location of the Hudson River plume as it propagates along the coast. The long-range network is used by the U.S. Coast Guard for Search And Rescue and by the NOAA HazMat Response Team in response to potential oil spills. In a dedicated 1-month duration test of Rutgers long-range CODAR network and the Coast Guard's new SAROPS planning tool, use of the CODAR surface current maps over existing methodologies were found to significantly improve the efficiency of Search And Rescue activities. When CODAR surface currents were used as input, the SAROPS search areas were reduced in size, and the drifter targets deployed were more consistently found within the tool's projected search areas.

The Rutgers network is also being used to improve the distribution of surface wave observations along the New Jersey coast. Since surface waves depend on the smaller secondary sidelobes of the Bragg peaks, the observational range for waves is reduced compared to the range for currents. Nevertheless, CODAR HF Radars provide an important gap filling dataset for NOAA surf zone forecasts of rip currents. Rip currents depend on the nearshore wave and current environment, which are more highly variable as you approach the coast. Rutgers displays the nearshore waves and currents

from its CODAR systems on the R.U. COOL website, and this data is then used by the NOAA National Weather Service regional office in Mount Holly to improve their rip current forecasts. Since HF radars are already distributed along the coast, Rutgers nearshore wave and current products can be used to reduce the number of wave buoys that must be deployed. The annual cost of maintaining an HF radar shore site is about one-tenth of the cost of maintaining an offshore buoy.

### **Vessel Tracking Applications**

Two technologies presently are in general use for wide-area surveillance vessel tracking applications. Satellite radars provide global coverage but their updating frequency is limited by their revisit intervals, typically twice per day for polar orbiting satellites in low earth orbit. This limits their operational effectiveness to vessels that are still far out at sea. Microwave radars provide many rapid updates every second, but their range is limited by line-of-sight to the horizon. Vessels or low flying aircraft can hide from microwave radars by using the curvature of the earth to fly or sail under the radar. Microwave radars therefore provide excellent coverage nearshore. In contrast to microwaves, HF radio waves can travel long distances over the salty ocean as a groundwave, following the curvature of the earth where it can scatter off of targets that are over the horizon and otherwise hidden from view. HF radar with its intermediate over-the-horizon view and its intermediate updating intervals of several times per minute is the only gap filling technology that could provide coverage between the two existing microwave and satellite technologies. This potential is recognized by the Office of Naval Research, the DoD Counter NarcoTerrorism Program Office, the Department of Homeland Security and the U.S. Coast Guard. With funding provided and coordinated by ONR, CNTPO, and DHS, and in collaboration with the U.S. Coast Guard, the Rutgers-CODAR academic-industry partnership has developed an abandoned Nike missile site at Sandy Hook, New Jersey into the world's most extensive HF radar tesbed for vessel tracking. At Sandy Hook, Rutgers currently operates compact CODAR HF radars for vessel tracking at 5, 13, and 25 MHz.

Trade off studies indicate that a distributed network of many compact, inexpensive, low power HF radars is a less risky approach than the alternative approach of a smaller sparse network of larger, more expensive, high power HF radars. One of the issues in favor of the distributed network is countermeasures. A vessel can easily hide in the high energy Bragg peak associated with the surface waves simply by making its speed relative to the radar the same as the scattering ocean waves. This can be achieved for a known radar location using a simple hand-held multi-band radio tuned to the HF radar signal to determine its frequency, and a pocket calculator with a square-root function to calculate the desired vessel speed. About a \$50 Radio Shack purchase is all that is required to defeat a multi-million dollar investment in a single radar. However, it is impossible for a ship to simultaneously hide in the Bragg peak of two radars with overlapping coverage.

Joint Rutgers University - CODAR Ocean Sensors partnership projects to develop the dual use vessel tracking and environmental capabilities of compact CODAR HF radars have been funded by ONR, CNTPO and DHS. ONR sponsored the initial tests to

demonstrate the detection and tracking of large vessels with HF radar. CNTPO sponsored a similar series of test for small, fast vessels. One objective of both projects was to use the existing low powered compact CODAR systems to estimate the various terms in the Radar Equation that would enable it to be used to estimate performance for different transmit power and receiver directivities. One result of this study was the CNTPO funding of the development of a compact Superdirective antenna that has now been installed at the Sandy Hook testbed. The Superdirective concept applied here uses 9 antenna elements arranged in a circle on top of a pole to achieve the same directivity as a linear array 100s of meters long. Tests of the Superdirective concept at Sandy Hook are anticipated to lead to the development of a mobile Superdirective receiver that can be moved around the Caribbean for law enforcement purposes. DHS has funded the development of a transmitter buoy that will be multi-statically coupled to the CNTPO Superdirective antenna. Mono-static operation implies that the HF radar transmitter is in the same location as the receiver. Multi-static operation means that the receiver is gathering data from every transmitter in view, even if they are not co-located. The DHS concept is to place additional radar transmitters offshore on buoys that will extend the useful range further offshore and provide multiple looks at vessels over wide regions. The working concept is to implement a multi-static distributed network of many inexpensive compact radars for vessel tracking and environmental data collection.

### **Key Needs**

Despite these successful demonstrations, obstacles still exist to the more widespread operational use of HF radar current and wave environmental products. Most U.S. HF Radar networks are operated by universities. Funding for operations and maintenance of the networks, including the extensive Rutgers CODAR network, presently depends on the research grant writing abilities of a few scientists. The Coast Guard cannot depend on the inevitable up and down cycles of research funding for an operational dataset. For the Coast Guard to adopt CODAR HF Radar as an operational input to SAROPS, dedicated operations and maintenance costs for the existing networks would have to be identified. In addition, capital costs for the acquisition of gap filling radars would be required to ensure that the data was available over the full area of interest. A second obstacle is the need to run the HF radar datasets through a NOAA Quality Assurance/Quality Control (QA/QC) program so that it receives the full liability protection of the U.S. government. Until this is done, many commercial groups such as shipping companies or harbor pilots will not use the data because of the potential for litigation. Many of the necessary QA/QC procedures already exist within the NOAA PORTS and NOAA NDBC systems, but require additional funding for NOAA personnel and HF radar operators like Rutgers to work together to implement the procedures on this new datastream.

The potential for collaboration between agencies is high. In 2003, Ocean.US founded the Surface Current Mapping Initiative Steering Committee to begin development of a plan for a National HF radar network as part of the U.S Integrated Ocean Observing System (IOOS). In 2005, Dr. Richard Spinrad, Assistant Administrator for NOAA contacted Admiral R. Dennis Sirois, Commandant of the Coast Guard proposing the two agencies work together to further the development of HF Radar as a

national network. Two items key collaborative efforts would be the use of existing Coast Guard coastal properties as potential shore sites for HF radars, and collaboration in an effort to request the FCC to grant a primary license for HF radars in segments of the broadcast spectrum. Presently HF radar operators use secondary FCC broadcasts licenses on a not to interfere basis. This requires HF radar operators to search for open frequency bands with little noise, and occasionally move to different frequencies in response to others. A national operational network would require primary licenses to ensure its continuous availability.

A national HF radar network is likely to eventually be implemented based on the proven usefulness of the current mapping data alone. A plan for vessel tracking that leverages off this network is possible based on the research initiated at the Sandy Hook test bed. Superdirective antennas acting in multi-static mode can be deployed to listen in on the existing broadcast network for vessel tracking. Where necessary, the network can be augmented with additional transmitters deployed on shore or on buoys. Additional tasks to accelerate this transition are the continued refinement and testing of new shore and buoy based hardware at the Sandy Hook testbed, continued development and coupling of multiple vessel detection algorithms, and the implementation of tracking software that fits vessel tracks to the detection data then interfaces the tracks with the existing user interfaces of the Maritime Domain Awareness system environment. The Norwegian military has expressed interest in collaborating with the U.S. to further the operational integration of dual-use Compact HF Radars for Maritime Domain Awareness.